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APPLICATION FOR UNITED STATES LETTERS PATENT

FOR

A METHOD FOR RESISTIVITY ANISOTROPY DETERMINATION IN CONDUCTIVE BOREHOLE ENVIRONMENTS

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CROSS REFERENCES TO RELATED APPLICATIONS

This application claims priority from United States Provisional Patent Application Ser. No. 60/414,175 filed on 27 September 2002.

BACKGROUND OF THE INVENTION

1. Field of the Invention

[0001] The invention is related generally to resistivity anisotropy interpretation systems and methods for well logging applications. More specifically, the invention is a method of data inversion for determination of formation parameters and for a description of reservoirs.

2. Background of the Art

[0002] Electromagnetic induction and wave propagation logging tools are commonly used for determining electrical properties of formations surrounding a borehole. These logging tools give measurements of apparent resistivity (or conductivity) of the formation that, when properly interpreted, are diagnostic of the petrophysical properties of the formation and the fluids therein. Normally, wells drilled with non-conductive oil-based mud (OBM) provide an ideal environment for induction logging tools, such as the 3DEX[SM]. However, in some environments, the drilling industry is turning from the use of OBM to environmentally sensitive water-based mud (WBM) systems. Highly conductive WBM tends to limit the effective dynamic range of formation measurements made with any induction logging tool.

[0003] The physical principles of electromagnetic induction resistivity well logging are described, for example, in H. G. Doll, Introduction to Induction Logging and Application to Logging of Wells Drilled with OBM, Journal of Petroleum Technology, vol. 1, p.148, Society of Petroleum Engineers, Richardson Tex. (1949). Many improvements and modifications to electromagnetic induction resistivity instruments have been devised since publication of the Doll reference, supra. Examples of such modifications and improvements can be found, for example, in U.S. Pat. No. 4,837,517 issued to *Barber*; U.S. Pat. No. 5,157,605 issued to *Chandler* et al, and U.S. Pat. No. 5,452,761 issued to *Beard* et al.

[0004] United States Patent 5,452,761 to *Beard* et al., the contents of which are fully incorporated herein by reference, discloses an apparatus and method for digitally processing signals received by an induction logging tool comprising a transmitter and a plurality of receivers. An oscillating signal is provided to the transmitter, which causes eddy currents to flow in a surrounding formation. The magnitudes of the eddy currents are proportional to the conductivity of the formation. The eddy currents in turn induce voltages in the receivers. The received voltages are digitized at a sampling rate well above the maximum frequency of interest. The digitizing window is synchronized to a cycle of the oscillating current signal. Corresponding samples obtained in each cycle are cumulatively summed over a large number of such cycles. The summed samples form a stacked signal. Stacked signals generated for corresponding receiver coils are transmitted to a computer for spectral analysis. Transmitting the stacked signals, and not all the individually sampled signals, reduces the amount of data that needs to be stored or

transmitted. A Fourier analysis is performed of the stacked signals to derive the amplitudes of in-phase and quadrature components of the receiver voltages at the frequencies of interest. From the component amplitudes, the conductivity of the formation can be accurately derived.

[0005] A limitation to the electromagnetic induction resistivity well logging instruments such as that discussed in *Beard et al.* '761 is that they typically include transmitter coils and receiver coils wound so that the magnetic moments of these coils are substantially parallel only to the axis of the instrument. Eddy currents are induced in the earth formations from the magnetic field generated by the transmitter coil, and in the induction instruments known in the art, these eddy currents tend to flow in ground loops which are substantially perpendicular to the axis of the instrument. Voltages are then induced in the receiver coils related to the magnitude of the eddy currents. Certain earth formations, however, consist of thin layers of electrically conductive materials interleaved with thin layers of substantially non-conductive material. The response of the typical electromagnetic induction resistivity well logging instrument will be largely dependent on the conductivity of the conductive layers when the layers are substantially parallel to the flow path of the eddy currents. The substantially non-conductive layers will contribute only a small amount to the overall response of the instrument and therefore their presence will typically be masked by the presence of the conductive layers. The non-conductive layers, however, are the ones which are typically hydrocarbon-bearing and are of the most interest to the instrument user. Some earth formations which might be of commercial interest therefore may be overlooked by

interpreting a well log made using the electromagnetic induction resistivity well logging instruments known in the art.

[0006] The effects of formation anisotropy on resistivity logging measurements have long been recognized. *Kunz and Moran* studied the anisotropic effect on the response of a conventional logging device in a borehole perpendicular to the bedding plane of thick anisotropic bed. *Moran and Gianzero* extended this work to accommodate an arbitrary orientation of the borehole to the bedding planes.

[0007] *Rosthal* (U.S. Pat. No. 5,329,448) discloses a method for determining the horizontal and vertical conductivities from a propagation or induction well logging device. The method assumes that the angle between the borehole axis and the normal to the bedding plane is known. Conductivity estimates are obtained by two methods. The first method measures the attenuation of the amplitude of the received signal between two receivers and derives a first estimate of conductivity from this attenuation. The second method measures the phase difference between the received signals at two receivers and derives a second estimate of conductivity from this phase shift. Two estimates are used to give the starting estimate of a conductivity model and based on this model. An attenuation and a phase shift for the two receivers are calculated. An iterative scheme is then used to update the initial conductivity model until a good match is obtained between the model output and the actual measured attenuation and phase shift.

[0008] United States Patent 6,147,496 to *Strack* et al. teaches the use of an induction logging tool in which at least one transmitter and at least one receiver are oriented in

orthogonal directions. By operating the tool at two different frequencies, it is possible to substantially reduce the effect of invasion and to determine the orientation of the tool to the bedding planes Received signals can be written as a series expansion in the frequency, which series expansion contains a term linear in the frequency which is mainly determined by the conductivity in the wellbore region. By combining the equation describing the series expansion of the signals in such a manner that the term linear in the frequency is eliminated, a new set of equations is obtained from which the influence of the wellbore region is virtually eliminated. .

[0009] United States Patent 5,999,883 issued to *Gupta et al*, (the "Gupta patent"), the contents of which are fully incorporated herein by reference, discloses a method for determination of the horizontal and vertical conductivity of anisotropic earth formations. Electromagnetic induction signals induced by induction transmitters oriented along three mutually orthogonal axes are measured. One of the mutually orthogonal axes is substantially parallel to a logging instrument axis. The electromagnetic induction signals are measured using first receivers each having a magnetic moment parallel to one of the orthogonal axes and using second receivers each having a magnetic moment perpendicular to one of the orthogonal axes which is also perpendicular to the instrument axis. A relative angle of rotation of the perpendicular one of the orthogonal axes is calculated from the receiver signals measured perpendicular to the instrument axis. An intermediate measurement tensor is calculated by rotating magnitudes of the receiver signals through a negative of the angle of rotation. A relative angle of inclination of one of the orthogonal axes which is parallel to the axis of the instrument is calculated, from

the rotated magnitudes, with respect to a direction of the vertical conductivity. The rotated magnitudes are rotated through a negative of the angle of inclination. Horizontal conductivity is calculated from the magnitudes of the receiver signals after the second rotation. An anisotropy parameter is calculated from the receiver signal magnitudes after the second rotation. Vertical conductivity is calculated from the horizontal conductivity and the anisotropy parameter.

[0010] U. S. Patent No. 5,889,729 issued to Frenkel et al., the contents of which are fully incorporated herein by reference, discloses a method for acquiring and interpreting wellbore logging data and a method for such interpretation which is significantly faster than previously known methods and which can be used at a well site. Said system produces a final earth model of part of an earth formation having one or more layers. The method includes, in one aspect, generating an initial earth model based on raw data produced by a wellbore logging tool at a location in a borehole through the earth, performing 2-D forward modeling on the initial earth model to produce an interim earth model that includes a set of synthetic tool responses data for the wellbore logging tool, correcting measurements in each layer for shoulder-bed effect, and comparing the synthetic tool response data to the raw data to determine whether there is misfit between them. Various methods of forward modeling can be performed in the case of misfit. The method of Frenkel '729 can be used for any resistivity logging data.

[0011] A multi-component device is discussed in U.S. Patent Application No. 10/091,310 by *Zhang* et al, having the same assignee as the present application and the contents of which are incorporated herein by reference. This tool is marketed under the

name 3DEX^{SM} by Baker Hughes, Inc. The 3DEX^{SM} device contains three transmitters and three receivers directed along orthogonal axes (x, y, z) with the z-component along the longitudinal axis of the drilling tool. The 3DEX^{SM} tool measures three principal components H_{xx} , H_{yy}, H_{zz} and two cross-components H_{xy} and H_{xz}. The 3DEX^{SM} device gives knowledge of resistivities and provides a process for general inversion of data. 3DEX^{SM} is useful in determining orientation, given a sufficient selection of initial conditions. The 3DEX^{SM} device collects data from the non-invaded zone to put in its model. Sensitivity to the initial conditions used in its data inversion affects the 3DEX^{SM} device. There is a need to provide a method of 3DEX^{SM} data interpretation.

[0012] Inversion processing of the 3DEX induction data allows the computation of both horizontal (R_h) and vertical (R_v) resistivities, thus allowing the determination of the formation resistivity anisotropy ratio ($\lambda = R_v / R_h$). Incorporation of these 3DEX data interpretation results in an enhanced shaly-sand, tensor resistivity petrophysical analysis, leads to reduced evaluation uncertainties and may result in a significant increase in calculated hydrocarbon-in-place reserves over estimates obtained with conventional methodologies. As shown in Frenkel '729, the 2-D inversion problem is subdivided into a sequence of smaller 1-D problems, thereby reducing computing time. For the 2-D inversion process, the vertical magnetic field component, H_{zz}, of the 3DEX data depends only on the horizontal resistivity, R_h. Therefore, it is possible to perform rapid sequential or even parallel 3DEX data inversion for both R_h and R_v. This can lead immediately to a calculation of resistive anisotropy.

[0013] Another technique used in oil exploration is based on galvanic-type well logging measurements. Among these measurements are the Laterolog, Microlaterolog, Array Lateral Log, and other tools.

[0014] The Laterolog and Microlaterolog are taught in Doll, H.G., "The Laterolog", Paper 3198, in Transactions of the AIME, v 192, p. 305-316, 1951, and in Doll, H.G., "The Microlaterolog", Paper 3492, in Transactions of the AIME, v 198, p. 17-32, respectively. Generally, the Laterolog is an electrode device with multiple current electrodes configured in several different ways to produce several different responses. A current-emitting and current-return electrodes (A and B) are placed close together on the sonde, with a measure electrode (M) several feet away, and a measure return (N) far away. This arrangement is sensitive to the potential gradient between A and B.

[0015] The Array Lateral Log technology of data measurements and interpretation is taught in *Hakvoort* et al. paper "Field Measurements and Inversion Results of the High-Definition Lateral Log", Paper C, in Transactions of the SPWLA, 1998. It describes a differential array instrument and a method for determining selected parameters of an earth formation surrounding a borehole. This instrument includes a mandrel carrying a single source electrode for injecting an electrical current of a predetermined value into the formation surrounding the borehole, and an array of measurement electrodes uniformly and vertically spaced from the source electrode along the instrument mandrel. The plurality of the Array Lateral Log measurements may be correlated to a plurality of values representative of the selected formation parameters. The plurality of values

representative of the selected formation parameters may provide a profile of the selected parameters over an increasing radial distance from the borehole.

[0016] In case of highly conductive borehole environments, we cannot neglect the borehole and invaded zone effects in any 3DEX-based data interpretation procedures. There is a need for a method for determination of a stable and unique anisotropy solution in highly conductive borehole environments. The present invention satisfies this need.

SUMMARY OF THE INVENTION

[0017] The invention is a method of determining a parameter of interest in an anisotropic earth formation in a conductive wellbore environment. The method of the invention described herein evaluates resistivity anisotropy. Data are acquired from a galvanic measuring device responsive primarily to parameters of an invaded zone and an uncontaminated zone surrounding the wellbore. Also, a multi-component device acquires measurement data responsive primarily to vertical and horizontal resistivity of the earth formation. The data acquired from a galvanic measuring device are inverted and upon inversion, enable the creation of a layered model of the invaded zone and the uncontaminated zones. Results of the model enable evaluation of formation resistivity data acquired from the deep-reading multi-component measuring device. The galvanic data may be acquired using a High-Definition Lateral Log and Microlaterolog (HDLL/MLL) or Dual Laterolog and Microlaterolog (DLL/MLL) devices, while the multi-component data is preferably acquired using a 3DEX^{SM} device, with 3DEX^{SM} data being acquired simultaneously with data from the galvanic logging device. In another

embodiment, HDLL/MLL or DLL/MLL measurements can be obtained separately. Inverted data from multi-component measurements are compared with the output of a model. Output of the model can be obtained from any forward modeling program, such as, for instance, a finite-difference modeling program.

[0018] The method of the invention is employable at an arbitrary angle of inclination. An orientation device conveyed on the logging tool enables determining the toolface angle. A magnetometer, for example, can be employed as said orientation device.

BRIEF DESCRIPTION OF THE DRAWINGS

[0019] FIG. **1** (prior art) shows a physical layout of the three transmitter coils and three receiver coils of a multi-component logging tool (3DEX) suitable for use with the present invention.

FIGS. **2a – 2d** show responses of the H_{xx} component of a multi-component tool for two environmental conditions, with and without borehole and invasion, and at single and dual frequencies.

FIG. **3** (prior art) shows a galvanic logging instrument suitable for use with the present invention

FIG. **4** shows a flowchart of the method of the present invention.

FIG. **5** shows an earth model example used in the present invention.

FIGs. 6a and 6b show examples of comparison of the method of the present invention with a prior art method.

FIG. 7 shows an example of a comparison of results obtained over a depth interval in a well using the method of the present invention with a prior art method.

FIG. 8 shows a string of tools suitable for use with the present invention

DETAILED DESCRIPTION OF THE INVENTION

[0020] Figure **1** shows the configuration of transmitter coils and receiver coils in an embodiment of the 3Dexplorer^{SM} (3DEX^{SM}) induction logging instrument of Baker Hughes Incorporated. Three transmitters **101, 103,** and **105** that are referred to as the T_x, T_z, and T_y transmitters are placed with their normals substantially orthogonal to each other, in the order shown. The three transmitters induce magnetic fields in three spatial directions. The subscripts (x, y, z) indicate an orthogonal system substantially defined by the directions of the normals to the transmitters. The z-axis is chosen to be substantially parallel to the longitudinal axis of the tool, while the x-axis and y-axis are mutually perpendicular directions lying in the plane transverse to the longitudinal axis. Corresponding to each transmitter **101, 103,** and **105** are associated receivers **107, 109,** and **111**, referred to as the R_x, R_z, and R_y receivers, aligned along the orthogonal system defined by the transmitter normals, placed in the order shown in Figure **1**. R_x, R_z, and R_y

are responsible for measuring the corresponding magnetic fields H_{xx}, H_{zz}, and H_{yy}. In this nominalization of the magnetic fields, the first index indicates the direction of the transmitter and the second index indicates the direction of the receiver. In addition, the receivers R_y and R_z, placed in the order shown, correspondingly labeled **113** and **115**, measure two cross-components, H_{xy} and H_{xz}, of the magnetic field produced by the T_x transmitter (**101**).

[0021] Dip angle is provided to 3DEX[SM] measurements by various methods, such as magnetometers. Knowledge of dip angle enables the method of the invention to operate both in vertical boreholes and in deviated boreholes. In a deviated borehole, orientation of the tool enables obtaining the tool face angle.

[0022] Figures 2a – 2d illustrate the influence of the conductive borehole and of invasion on single frequency and dual frequency logs of the H_{xx} component of the 3DEX[SM]. The formation parameters or the model in Figure **2a** are as follows: the borehole diameter is Ø = 9", and the borehole is filled with conductive mud $R_m = 0.04\ \Omega\cdot\mathrm{m}$, the invasion is shallow, ($L_{xo} = 4"$) and conductive ($R_{xo} = 0.1\ \Omega\cdot\mathrm{m}$). Figure **2b** shows the modeling results for the single frequency and dual frequency logs for two low frequencies: 20 and 40 kHz (single) and 20/40 and 40/80 kHz (dual). The main purpose of a dual frequency transformation of the single frequency data is to reduce the near-borehole effect. Application of the dual frequency in the interpretation process is critical to logging a borehole with a very conductive mud. The formula for the dual frequency (*DF*) transformation is

$$H_{DF}(f_1, f_2) = H(f_1) - (f_1/f_2)/H(f_2)$$

where $H(f_1)$ and $H(f_2)$ are the magnetic fields measured at the single frequencies f_1 and f_2, respectively. The dual frequency transformation slightly reduces the vertical resolution of the interpreted results and is most effective at lower frequencies.

[0023] In two left most tracks of Figure **2b** is shown the single frequency logs for the H_{xx} component. The two right most tracks show the dual frequency logs for the same H_{xx} component. The calculations are performed with a three-layer, two-dimensional earth model (solid curves) and a simple horizontally layered (1-D) earth model (dashed curves). Each layer of this horizontally layered earth model consists of an uncontaminated zone only, i.e., neither a borehole nor invasion are present. It is observed that the near-wellbore effect is there, but it is relatively small.

[0024] The situation changes dramatically when the amount of conductive material at the wellbore increases due, for example, to a larger and more conductive borehole, and/or deeper conductive invasion. Figure **2c** presents a similar three-layer model with the 12" diameter borehole filled with a more conductive mud ($R_m = 0.02\ \Omega\cdot m$). Here, the invasion depth is L_{xo} = 12", and the invaded zone has the same resistivity, $R_{xo} = 0.1\ \Omega\cdot m$ (see the left track), as before. Figure **2d** presents the modeling results for the same single frequency and dual frequency components for the model of Figure **2c**.

[0025] It is quite evident the dual frequency logs provide a lower vertical resolution than the corresponding SF logs, and the near-wellbore conductive zone has a strong effect on both the single frequency and dual frequency logs (compare solid and dashed logs in the four right most tracks of Figure **2b**).

[0026] It is precisely for this reason that, in case of highly conductive borehole environments, we cannot neglect the borehole and invaded zone effects in any 3DEX^{SM}-based data interpretation procedures.

[0027] To address this physical limitation in the induction data, the present invention is a new interpretation method that combines in a single interpretation scheme both galvanic and induction logging data so as to accurately recover formation resistivity anisotropy.

[0028] U.S. Patent No. 6,060,885 to *Tabarovsky* et al, the contents of which are incorporated herein by reference, discloses a galvanic measurement device for determining resistivity of a geological formation surrounding a borehole. As shown in Figure **3**, the instrument **410** includes a mandrel **412** carrying a single source electrode **532** and a plurality of measuring electrodes **433**, **435**, **436**, **437**, etc. vertically spaced in equal increments along the axis of the mandrel **412**. The number of measuring electrodes chosen for this example is 36, which including the source electrode, makes a total of 37 electrodes which are marked **1-37** in Figure **3**. In the embodiment of Figure **3**, a group **434** of three successive electrodes **433**, **435**, and **436** are used to obtain measurements, for example, of first potential difference, D_1. For measurement of said potential difference, the source electrode **432** injects an electrical current of a predetermined value into the formation and it is received by successive lower vertical groups of three electrodes as at **434'** and **434''**. The 36 measuring electrodes produce 12 measurements from successive electrode groups **434**, **434'**, **434''**, etc. for measuring the first potential difference, thus: at **434**-$D_1^{(1)}$, at **434'**-$D_1^{(j)}$, and at **434''**-$D_1^{(12)}$. Examining the electrode

group identified as **534'**, the first vertically disposed measurement electrode is identified as j-1 (**433'**), the center electrode is identified as j (**435'**), and the third or lower electrode is identified as j+1 (**536'**). The first potential difference $D_1^{(j)}$ is calculated as:

$$D_1^{(j)} = \frac{V_{j+1} - V_{j-1}}{2}.$$

Accordingly, each measurement unit provides first differences, D_1 at each depth level. The differential conductance is also available at each logging depth.

[0029] The application of the multi-component induction tool supplies the log analyst with unique information to determine formation resistivity anisotropy. To overcome the challenge of limited effective dynamic range caused by WBM systems, the multi-component measuring device is logged in combination with a galvanic tool. As an example, HDLL/MLL or DLL/MLL devices can be used as the galvanic measuring devices, and 3DEX^{SM} can be used as a multi-component measuring device. However, use of any of these tools is not meant as a restriction on the scope of the invention. Inversion-based data interpretation proceeds by first determining the formation resistivity structure of the near wellbore environment using the galvanic measuring device, and then determining the formation resistivity anisotropy of the undisturbed zone using these determined results from the galvanic device and the deep induction measurements of the multi-component measuring device. The measurements provided by the galvanic measuring tool enable evaluation of the drilling fluid invasion profile to the inversion of multi-component measurement data.

[0030] The method of the invention is outlined in more detail in Figure **4**. In Box **501**, raw data is collected from at least one galvanic measuring device and also from a multi-component measuring device. The galvanic measuring device generally provides information of the structure of the conductive near wellbore environment, while the multi-component measuring device generally obtains information on parameters far from the measurement tool As shown in Figure. **5**, subsurface of the earth is characterized by a plurality of layers **601a, 601b, . . ., 601i**. The layers have thicknesses denoted by $h_1, h_2, \ldots h_i$. The horizontal and vertical resistivities in the layers are denoted by $R_{h1}, R_{h2}, \ldots R_{hi}$ and $R_{v1}, R_{v2}, \ldots R_{vi}$ respectively. Equivalently, the model may be defined in terms of conductivities (reciprocal of resistivity). The borehole is indicated by **602** and associated with each of the layers are invaded zones in the vicinity of the borehole wherein borehole fluid has invaded the formation and altered is properties so that the electrical properties are not the same as in the uninvaded portion of the formation. The invaded zones have lengths $L_{x01}, L_{x02}, \ldots L_{x0i}$ extending away from the borehole. The resistivities in the invaded zones are altered to values $R_{x01}, R_{x02}, \ldots R_{x0i}$. In the embodiment of the invention discussed here, the invaded zones are assumed to be isotropic while an alternate embodiment of the invention includes invaded zones that are anisotropic, i.e., they have different horizontal and vertical resistivities. It should further be noted that the discussion of the invention herein may be made in terms of resistivities or conductivities (the reciprocal of resistivity). Parameters of isotropic invaded zone and horizontal resistivity of uncontaminated zone are assumed to be determined via inversion processing of the galvanic data.

[0031] Returning to Figure.**4**, a data inversion of galvanic measurement data is performed (Box **503**). In box **505**, an initial earth model for further anisotropy inversion using the 3DEX data is introduced having parameters defined corresponding to each layer of the borehole (i.e. diameter of borehole, Ø, resistivity of borehole fluid, R_m) and of invasion (i.e. length of invaded zone, L_{xo}, and resistivity of invaded zone, R_{xo}) and of horizontal resistivity R_h. The resistivity of borehole fluid can be provided previously, for instance, by the operator. The value of the diameter of the borehole could be determined using a suitable device such as a mechanical caliper or an acoustic calipert. In Box **507**, an inversion of deep 3DEX[SM] measurement data is undertaken using results from Box **505**. It is to be noted that the near-zone parameters, R_{xo} and L_{xo}, are not updated during the inversion at **507**. At this step, the 3DEX data inversion is performed to update previously determined horizontal resistivity R_h and define the vertical resistivity R_v. In Box **509**, an anisotropic earth model results, having anisotropy defined in each layer of the undisturbed zone. An example of the use of inversion for analysis of array induction logging data is given in "Rapid well-site 2-D inversion of full-spectrum array induction data," Transactions of the 1996 SPE Annual Technical Conference and Exhibition, paper SPE 36505). By use of the method of the present invention, parameters of interest such as the vertical and horizontal resistivities of the formation, layer thicknesses, and length and resistivity of the invaded zone may be determined.

[0032] Turning next to Figures. **6a** and **6b**, examples of results using the method of the present invention on simulated data and a comparison with a straightforward inversion of 3DEX data are shown. The mud resistivity for generating the simulated ata

was 0.02Ω –m. Fig. **6a** corresponds to a borehole diameter of 12 inches while Fig. **6b** is for a borehole diameter of 8 inches. The abscissa in each figure is the length of a simulated invasion zone. In both cases, the anisotropy factor was 4.0.

[0033] The dashed lines **651a** and **651b** are the results of prior art inversion (Dual frequency method) using only the 3DEX data. For the inversion, the initial values of the model parameters were within 10% of the true values. The solid lines **653a** and **653b** are the results of inversion using the method of the present invention, i.e., sequential inversions of the DLL and 3DEX data. Analysis of the inversion results shows that even for moderate anisotropy, in the presence of a highly conductive mud, the deeper the invasion zone, the greater the error in the prior art method.

[0034] **Fig. 7** shows inversion results for a short (30 ft.) depth interval. All depths are relative. The left track shows the caliper and the gamma ray logs. Tracks 2-3 show the results of the 3DEX inversion and tracks 4-5 show the results of the sequential HDLL and 3DEX inversion over the selected interval. The results are presented as blocky curves, which indicates the resistivity of the invaded zone, R_{x0}, the horizontal resistivity, R_h, the vertical formation resistivity, R_v, and the anisotropy λ. The depth of the invasion is, on average, $L_{x0} \approx 8 - 10$". The smoothest curve is tracks (2) and (4).

[0035] It is apparent that the 3DEX induction data inversion approach yields, on average, a 25% higher value of anisotropy (track 3) than the anisotropy obtained with the application of the sequential (HDLL) and induction (3DEX) inversion (tyrack 5). This calculation is in good agreement with results from **Fig. 6**.

[0036] An exemplary configuration of tools for use with the present invention is shown in Figure **8**. Shown in the figure is a rig **710** on the surface that is positioned over a subterranean formation of interest **712**. The rig **710** can be a part of a land or offshore a well production/construction facility. A wellbore **714** formed below the rig **710** includes a cased portion **716** and an open hole portion **718**. In certain instances (*e.g.*, during drilling, completion, work-over, etc.), a logging operation is conducted to collect information relating to the formation **712** and the wellbore **714**. Typically, a tool system **800** is conveyed downhole via a wireline **810** to measure one or more parameters of interest relating to the wellbore **714** and/or the formation **712**. The tool system **800** can include one or more modules **802 a,b**, each of which has a tool or a plurality of tools **804 a,b**, adapted to perform one or more downhole tasks. For use with the present invention, these modules could include, e.g., a 3DEX induction, and the other module could be the dual laterolog. The term "module" should be understood to be a device such as a sonde or sub that is suited to enclose, house, or otherwise support a device that is to be deployed into a wellbore. While two modules **802 a,b** and two associated tools **804 a,b,** are shown, it should be understood that a greater or fewer number may be used.

[0037] In certain embodiments, the tool system **800** can include telemetry equipment **850**, a local or downhole controller **852** and a downhole power supply **854**. The telemetry equipment **850** provides two-way communication for exchanging data signals between a surface controller **812** and the tool system **800** as well as for transmitting control signals from the surface processor **812** to the tool system **800**. The processing of the data may be done entirely downhole, entirely uphole, or a combination of the two. It

should further be noted that while the string of tools shown in Fig. 7 is conveyed on a wireline, conveyance may be done by coiled tubing in near horizontal boreholes.

[0038] The combination of galvanic and induction measurements can effectively extend the dynamic range of multi-component induction measurements, allowing the use of this technology in wells drilled with conductive WBM systems. The use of this information leads to significantly more accurate hydrocarbon-in-place estimates in electrically anisotropic laminated reservoirs.

[0039] With relatively minor modifications, the present invention may also be used in Measurement-While-Drilling (MWD) applications wherein the sensor modules are conveyed downhole on a drilling tubular such as a drillstring or coiled tubing.

[0040] While the foregoing disclosure is directed to the preferred embodiments of the invention, various modifications will be apparent to those skilled in the art. While specific embodiments of the microresistivity tool and induction logging tool have been discussed above, it is to be understood that the tools may be used either on a wireline or in an MWD environment. It is to be further understood that the anisotropy measurements discussed above with reference to an induction logging tool may also be obtained using a propagation resistivity tool. It is intended that all variations within the scope and spirit of the appended claims be embraced by the foregoing disclosure.